NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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A SIMPLE CALIBRATION PROCEDURE FOR COLOR CRT DISPLAYS

by

LT David F. Neri, MSC, USN

Naval Medical Research and Development Command
Research Work Unit M0100.001-5003

Released by:

C. A. HARVEY, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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SUMMARY PAGE

PROBLEM

To provide sonar display designers unfamiliar with color terminology and measurement a) some basic information on color specification and b) a simple color CRT calibration method to enable them to follow published guidelines in applying color to the newest generation of displays.

FINDINGS

A brief description of the internationally-recognized CIE system of color specification is provided, along with a convenient, straightforward, and easily implemented method for calibrating color CRTs to the level of accuracy needed in sonar display development applications.

APPLICATIONS

The CRT calibration procedure presented here requires specific equipment but is readily incorporated into computer software. With this capability, the sonar display designer is able to accurately reproduce specific colors recommended for use in displays by various guidelines and software programs.

ADMINISTRATIVE INFORMATION

This investigation was undertaken under Naval Medical Research and Development Command Work Unit M0100.001-5003 - "Enhanced performance with visual sonar displays." This report was submitted for review on 19 Jun 1988, approved for release on 14 Jul 1988, and designated as Naval Submarine Medical Research Laboratory Report Number 1118.

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Abstract

A simple calibration procedure for color CRT displays is described. It provides a convenient means of producing colors specified in terms of their chromaticity coordinates and luminance, as well as the inverse procedure -- determining the chromaticity and luminance of displayed colors to a reasonable degree of accuracy without direct measurement. It is intended for those with access to a spectroradiometer but with little or no background in color perception and measurement. A brief description of the commonly used 1931 CIE system of colorimetry is provided as background. References are provided for those desiring further information on the CIE system and issues affecting accurate color CRT calibration.

A Simple Calibration Procedure for Color CRT Displays

The increase in the use of color displays in recent years has resulted in many general recommendations for applying color appropriately and effectively (e.g. Conover & Kraft, 1958; DeMars, 1975; Gibson & Laycock, 1982; Krebs, Wolf, & Sandvig, 1978; Semple, Heapy, Conway, & Burnette, 1971; Silverstein, 1982; Teichner, Christ, & Corso, 1977; Wigert, 1982). Many of the tasks to which color coding has been applied are of the general type that sonar operators or other users of displays on submarines and ships might perform. Some of these tasks have involved visual search and identification (Carter, 1982; Carter & Cahill, 1979; Christ, 1975; Luder & Barber, 1984); others have dealt with the visibility of colored characters or the detection of colored targets on various backgrounds (Bruce & Foster, 1982; Eastman, 1968; Kinney & Culhane, 1978; Santucci, Menu, & Valot, 1982). A few studies have looked specifically at airborne applications of color coding (Gibson & Laycock, 1982; Luder & Barber, 1984; Semple et al., 1971; Silverstein, 1982); others were tailored to submarine applications (Butler & McKemie, 1974; Neri & Zannelli, 1984). Two issues relevant to navy display designers are addressed in many of these studies: how many colors to use and what they should be. The answers vary according to the many variables involved, including the hardware used, the perceptual task, and the viewing conditions. When it is desirable to pick colors that are widely separated in color space, there are now computer programs available which provide color sets of variable size using algorithms that manipulate

the color differences between members of the set (Silverstein, Lepkowski, Carter, & Carter, 1986; DeCorte, 1986a, 1986b).

A problem can arise, however, because many of the myriad guidelines pertaining to color usage presuppose a familiarity with the CIE (International Commission on Illumination) system of color specification. Further, these guidelines require a calibrated color CRT display in order to be implemented. The use of the word "calibrated" in this context means the capability to produce colors specified according to this CIE system of colorimetry. With a calibrated display, a color specified by one person in terms of its CIE coordinates and luminance can be exactly reproduced by another. While the use of calibrated displays has always been critical in precise visual research, it is now becoming more important with the increasing application of color displays. For the display designer who is familiar with color terminology and measurement and has a color-calibrated CRT display, the published guidance enables him to avoid time-consuming solutions based on trial and error, or simply what "looks best". However, to those without this familiarity or calibration capability, even the best-researched recommendations are useless. The purpose of this report is to provide enough familiarity with both the CIE system and calibration methodology to allow someone new to these areas to utilize the ever-growing literature.

For those interested in the finer points of color display calibration, there are excellent and thorough discussions of the relevant theoretical and technical issues (Cowan, 1983, 1987; Cowan & Rowell, 1986). There are also many excellent sources for basic information about color appearance and measurement (e.g. Billmeyer & Saltzman, 1981; Committee on Colorimetry

of the Optical Society of America, 1963; MacAdam, 1985; Wyszecki & Stiles, 1982) and color theory (e.g. Boynton, 1979; Hurvich, 1981; Wyszecki & Stiles, 1982). The detailed report of Merrifield & Silverstein (1986) includes much information about color usage and is specifically intended for those working with displays in an operational environment.

The goal of the present report is not to exhaustively examine all the variables that have been considered in the references above, but to fill a perceived gap by providing to navy display designers the bare essentials in background and tools which will enable them to calibrate a color CRT and then use published guidance in applying color. With a color monitor of reasonable stability and good overall quality, and the use of a spectroradiometer, the calibration procedure described below should be more than adequate. In fact, much of the limitation of any calibration method results from characteristics of the color monitor itself. Prior to describing the actual calibration method, there needs to be a brief description of the CIE system of color specification. For those interested in more information, there are both detailed accounts of the CIE system (Hardy, 1936; Wyszecki & Stiles, 1982) and relatively brief ones (Hurvich, 1981; MacAdam, 1985; Padgham & Saunders, 1975).

The 1931 CIE System of Color Specification

The CIE system was founded on the basic principle of color measurement that any color can be matched by a mixture of suitable amounts of three primary colors that are well-separated in the visible spectrum. In some instances a "negative" amount of one of the primaries is required, meaning that it must be added to the color to be matched. The idea behind this standardized system was to express any realizable color in terms of

relative amounts of a standard set of primaries. Many different primaries could serve the purpose, but for computational and graphical convenience, the CIE adopted three imaginary primaries designated **X**, **Y**, and **Z**. (See the Glossary for definitions of all the symbols used in this report). These primaries cannot be realized, but the transformation to them from any set of real primaries can be accomplished by linear algebra alone.

The next step was to determine the relative amounts of these standard imaginary primaries necessary to match each equal-energy wavelength of light in the visible spectrum. For these purposes the visible spectrum is defined as light with wavelengths from 380 to 780 nanometers (nm). The matching procedure was accomplished with real primaries and the results transformed to those that would occur with the use of the standard, imaginary primaries. The results of the matching procedure and transformation are known as the color-mixture functions for the 1931 CIE Standard Observer, shown in Figure 1. The relative amounts of the standard primaries needed for the matches are referred to as the spectral tristimulus values $\bar{x}$, $\bar{y}$, $\bar{z}$, with $\bar{x}$ representing the amount of the **X** primary, and so on. If each spectral tristimulus value for a particular wavelength, λ , is divided by the sum of the three values for that wavelength, the chromaticity of that wavelength is given:

$$x = \bar{x} / (\bar{x}+\bar{y}+\bar{z}) \quad (1a)$$

$$y = \bar{y} / (\bar{x}+\bar{y}+\bar{z}) \quad (1b)$$

$$z = \bar{z} / (\bar{x}+\bar{y}+\bar{z}). \quad (1c)$$

The values x, y and z are called chromaticity coordinates. A plot of the x and y chromaticities of all individual wavelengths in the visible

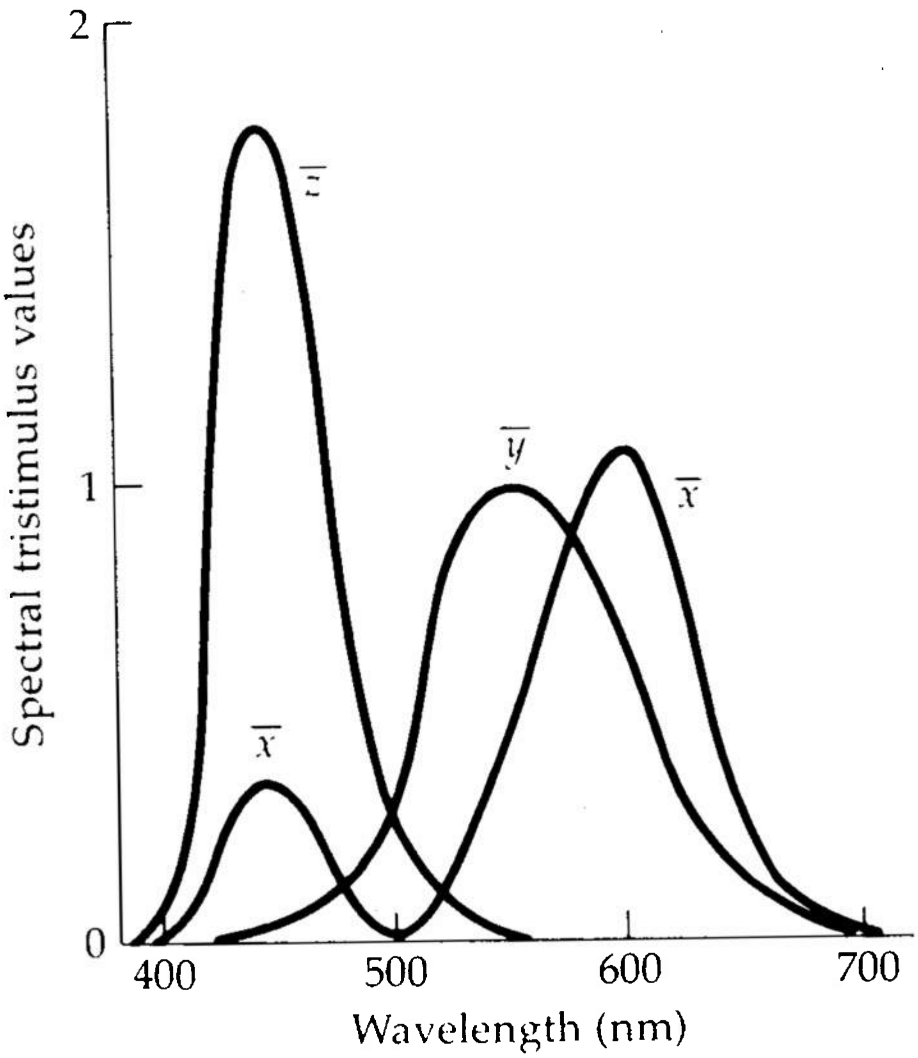

Figure 1. Color-mixture functions for the 1931 CIE Standard Observer. The spectral tristimulus values, $\bar{x}$, $\bar{y}$, and $\bar{z}$, represent the relative amounts of the primaries **X**, **Y**, and **Z**, respectively, needed to match equal-energy wavelengths.

spectrum is shown as the horseshoe-shaped curve in Figure 2, labelled 380 to 700 nm. All realizable colors, which consist of combinations of these wavelengths emitted or reflected, plot within the area circumscribed by this curve and the straight line connecting 380 and 700.

CRT displays produce self-luminous colors, and any self-luminous color consists of wavelengths of various energies throughout the visible spectrum. The emission spectrum of the color is denoted as E. To obtain the chromaticity of the color, we multiply its energy at each wavelength, from 380 to 780 nm, by each of the three spectral tristimulus values ($\bar{x}$, $\bar{y}$, $\bar{z}$) at each wavelength, and then sum the three sets of products. In effect, this weights the emitted energy by the sensitivity of the visual system. The results are called the tristimulus values (as opposed to *spectral* tristimulus values), and are designated X, Y, and Z. These are distinguished from the imaginary primaries, bold **X, Y,** and **Z**. This procedure is illustrated in Figure 3. The equations for the integration that describes this process are:

$$X = \int E_\lambda \, \bar{x}(\lambda) d\lambda \qquad (2a)$$

$$Y = \int E_\lambda \, \bar{y}(\lambda) d\lambda \qquad (2b)$$

$$Z = \int E_\lambda \, \bar{z}(\lambda) d\lambda . \qquad (2c)$$

The integration occurs over the range λ = 380 to 780 nm. These tristimulus values represent the amounts of the imaginary primaries necessary to match the color whose spectrum of emitted visible light is given by E. Thus X represents the amount of the **X** primary, and so on. The more familiar chromaticity coordinates (x,y) for such a color are defined,

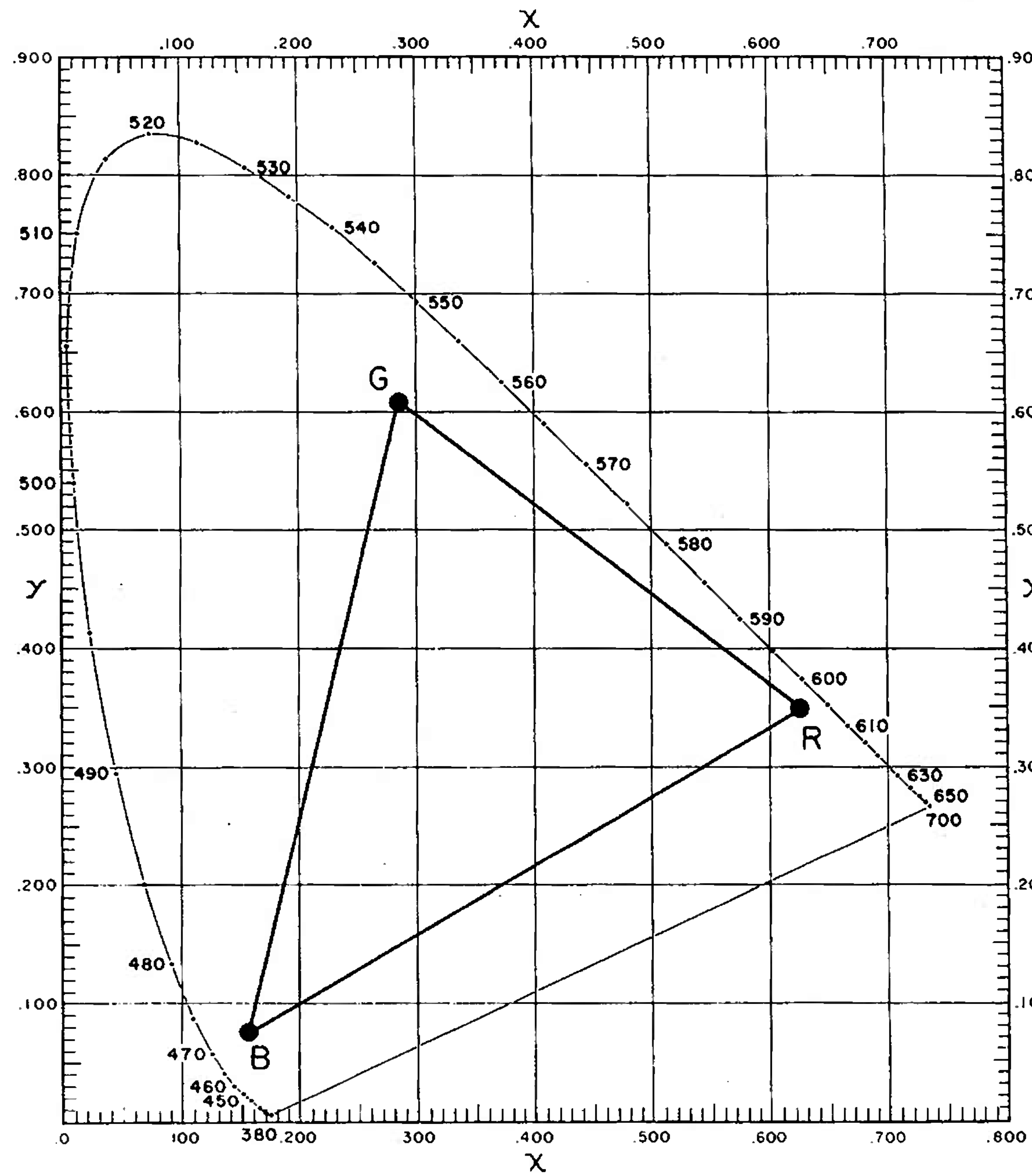

Figure 2. The 1931 CIE chromaticity diagram. The horseshoe-shaped curve represents the chromaticities of monochromatic light throughout the visible spectrum. The triangle **RGB** represents the color gamut of a typical CRT. Colors produced by the display are limited to the area of the triangle.

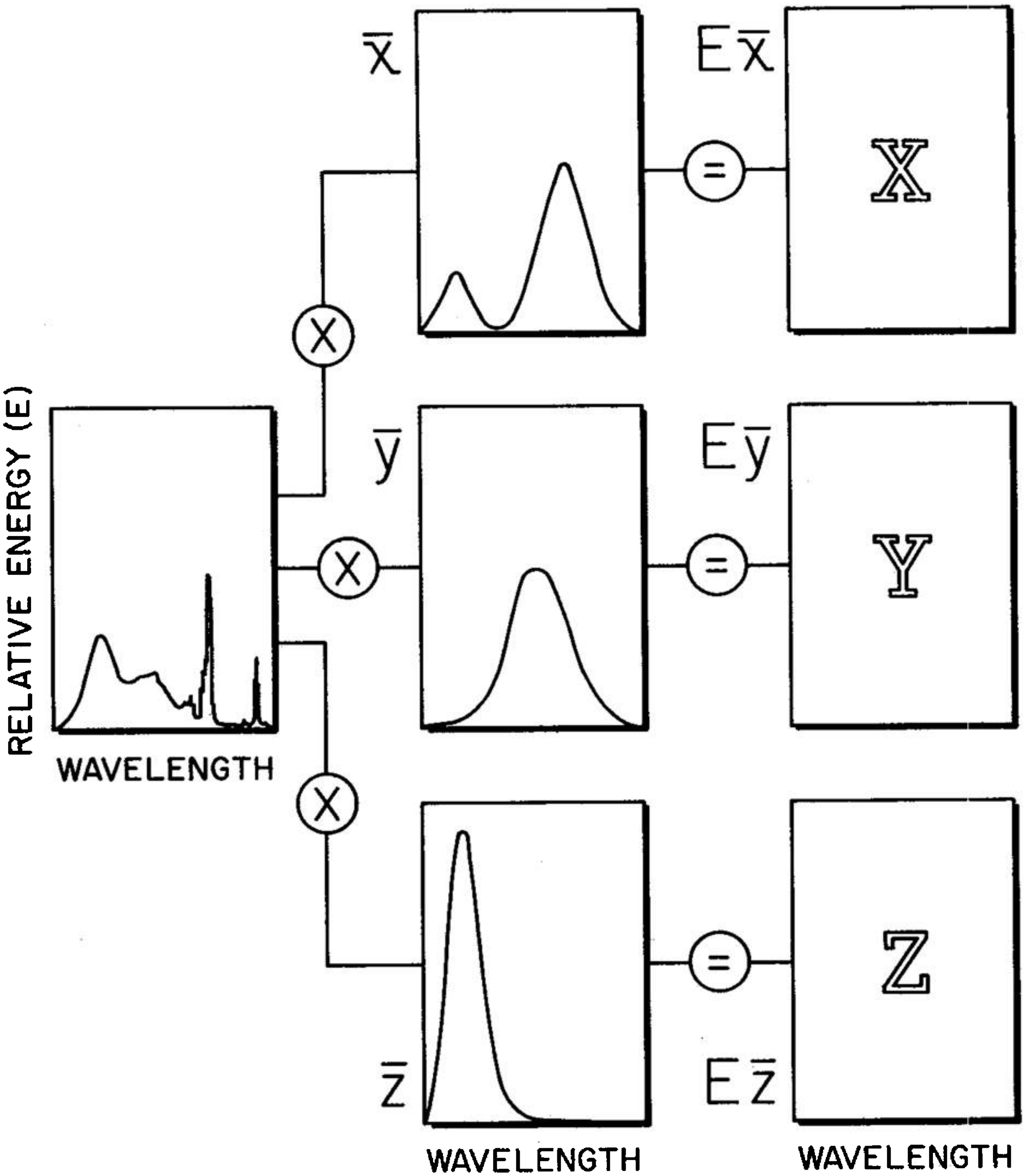

Figure 3. The CIE tristimulus values X, Y, and Z are obtained by multiplying, wavelength by wavelength, the relative energy (E) of a self-luminous display color and the spectral tristimulus values $\bar{x}$, $\bar{y}$, and $\bar{z}$, to give the curves $E\bar{x}$, $E\bar{y}$, and $E\bar{z}$ (not shown). The areas under such curves, appropriately normalized, are the X, Y, and Z tristimulus values. (After Billmeyer & Saltzman, 1981, p. 46).

analogously to those for the spectral colors above, as the relative amounts of the tristimulus values. Thus:

$$x = X / (X+Y+Z) \quad (3a)$$

$$y = Y / (X+Y+Z) \quad (3b)$$

$$z = Z / (X+Y+Z). \quad (3c)$$

Since $x + y + z$ must equal 1.0, it is sufficient and customary to report and use only the x and y coordinates. Once the chromaticity coordinates for a color have been calculated, that color can be plotted in Figure 2. Note that the chromaticity coordinates hold irrespective of the luminance of the color. However, the CIE chose its imaginary primaries such that the tristimulus value Y is proportional to $V(\lambda)$, the spectral luminosity function, which represents the response of the visual system to the total amount of power present in the visible spectrum. Thus Y is a measure of the color's light level. As a result, x, y, and Y completely specify the chromaticity and luminance of a color in a standardized, internationally recognized system.

Color CRT Calibration

The procedure to be described is a version of the model-dependent calibration method described in detail by Cowan (1987) and is also equivalent to the PLCC method described by Post & Calhoun (1987). It is a computational method which is simple to implement in software. However, to obtain the necessary degree of accuracy, a relatively expensive instrument, the spectroradiometer, is required. Use of the more readily available and less expensive filter-based photometer would most likely lead to inaccurate measurements of the blue phosphor which, in turn, would result in a large

systematic error along a yellow-blue axis in color space (W. B. Cowan, personal communication, June 1988). Cowan (1983) provides a solution to this problem with a gun balance and normalization procedure, but it represents an additional computational step. The trade-off is, therefore, one of a little extra expense in exchange for a little extra computational simplicity.

The present calibration is accomplished using the 1931 CIE system of colorimetry and its associated chromaticity space (Figure 2) discussed above. Further transformations necessary to describe colors in other spaces (e.g. 1976 CIE UCS) can then be carried out by additional computations. (See Robertson (1977) for a complete description of UCS). The calibration procedure will be broken down into its two logical parts which are described separately: 1) solving for the CIE chromaticity coordinates of any displayed color, and 2) performing the inverse operation of producing stimuli with desired CIE chromaticity coordinates. It is important to note that both procedures are based on the following assumptions and conditions drawn largely from Cowan (1987), which are probably met by most color monitors in most development applications.

<u>Assumptions</u>

o Gun independence. Any displayed color results from the simple additive mixture of the colors produced by each contributing electron gun.

o Phosphor constancy. The chromaticity of each phosphor remains constant despite variations in its intensity resulting from variations in voltage input to the gun.

o Temporal stability. The monitor can reproduce colors of the same chromaticity at different times, with the same voltage input to the guns.

o Spatial uniformity. The same voltage input to the guns produces colors of the same chromaticity at different locations on the screen.

Conditions

o Stable line voltage to color monitor.

o Constant settings of brightness and contrast knobs between calibrations.

o There must be either no measurable amount of light emitted from the CRT screen when the three guns are turned off, or one must use the correction for ambient light described below.

o There must be either no ambient light present during colorimetric measurements and during the display of colors resulting from the calibration, or one must use the correction for ambient light described below.

The assumptions of temporal stability and, especially, spatial uniformity have not been found to hold exactly, particularly for large separations in time and space. Restricting colors to locations near the center of the screen, and recalibrating frequently, will enhance the accuracy of the calibration results.

I. Determination of chromaticity and luminance of a displayed color.

One objective in calibrating a CRT display is to be able to determine the chromaticity and luminance of displayed colors without making cumbersome and time-consuming colorimetric measurements of each one. The chromaticity of a displayed color can be determined from 1) the stable chromaticities (x,y) of the three phosphors, and 2) the luminances of the three phosphors when combined to produce the color. In regard to the first requirement, the chromaticities of the phosphors need to be measured only infrequently with the spectroradiometer. These chromaticities constitute the corners of the triangle **RGB** in Figure 2. All the colors produced by the CRT are simply combinations of intensities of these phosphor primaries, and so their chromaticities fall within this triangle.

The second requirement introduces a problem because the phosphor luminances are not quickly and easily measured for all voltage values of the three guns. There are often at least 256 voltage values per gun, resulting in hundreds of measurements. However, with 256 values per gun, for example, it will suffice to perform no more than 30 luminance measurements spaced throughout the voltage range of each gun. In fact, Post & Calhoun (1987) have shown that about half that many measurements provide adequate accuracy. These data relating luminance to voltage are referred to here as the "calibration data", but the relationship is technically known as a gamma correction (Cowan, 1987).

The calibration data do not need to be collected frequently if the conditions listed above are met, and the monitor and other electronic equipment near it are not moved. Fortunately, the graphics system often provides a convenient way of collecting these data. Sometimes the voltage information is provided in the form of a triplet of numbers proportional to the three gun voltages used to display a color. For the sake of convenience and clarity, it will be assumed here that there is system output in the form of these numbers, or that whatever voltage information is provided by the system has been converted to them. For example, it is easiest to number 256 discrete voltage values per gun, in whatever form provided, from 0 to 255. These numbers, one for each of the three guns (and hence one for each of the red, green, and blue phosphors), will be referred to as the monitor coordinates, R, G, and B, respectively. As a result of these calibration measurements then, there now are data relating luminance to a subset of monitor coordinates for each of the three guns.

There are several approaches to obtaining the luminance associated with a given monitor coordinate that has not been specifically measured (see Post & Calhoun, 1987). One obvious and often recommended technique is to fit a function to these data. A typical function on non-normalized data is shown in Figure 4A, in this case for a green gun. Functions fitted to data of this type can indeed account for nearly all of the variance. But this can still be an unacceptable solution, because there are often noticeable inaccuracies in the fit, particularly at the lower values of the monitor coordinates. Of course one can then fit separate functions to different parts of the curve, but this requires further time and effort. An alternative is to perform a piece-wise linear interpolation between data points (Figure 4B). Post & Calhoun explicitly compared piece-wise linear interpolation with five other methods and also found the former to provide the best accuracy. To obtain any desired luminance value, a computer routine can perform a simple linear interpolation between the two monitor coordinates bracketing the one used to produce the color. This is done, of course, for each gun.

To summarize this general calibration procedure so far, for any displayed color the needed chromaticities of the CRT phosphors are known from infrequent spectroradiometric measurements. The particular luminance of each phosphor when producing the color is obtainable from the calibration data relating luminance to monitor coordinate for each gun. Specifically, these luminance values are obtained using a piece-wise linear interpolation computer routine.

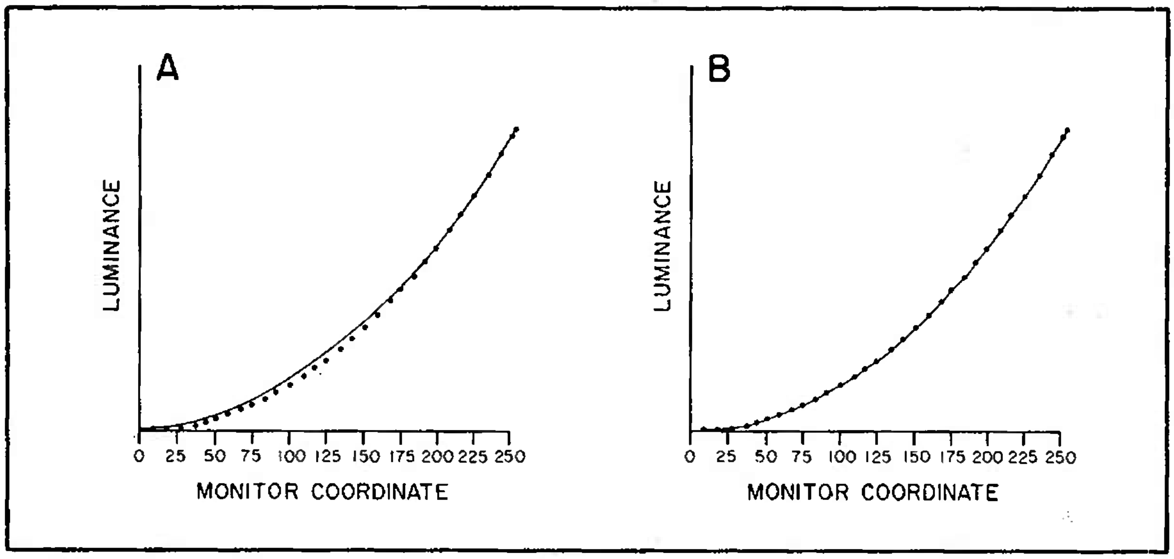

Figure 4. Calibration data relating luminance to monitor coordinate for a typical green gun with 256 intensity or voltage levels. A) A smooth gamma correction function fitted to the data points. B) The curve resulting from a piece-wise linear interpolation between successive data points.

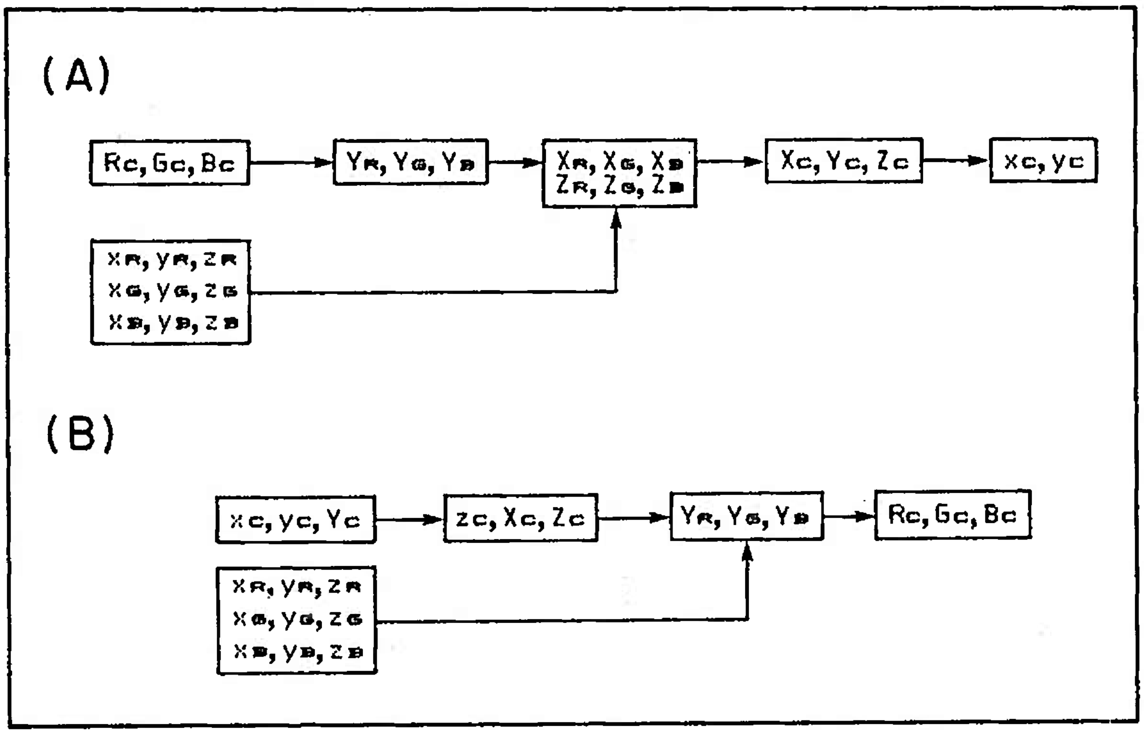

Figure 5. A) Diagram showing the order of calculation for determining the chromaticity and luminance of a displayed color. B) Diagram showing the order of calculation for determining the monitor coordinates needed to produce a specified chromaticity and luminance.

A. Ambient light correction.

When there is background light emitted by the CRT with all guns turned off, or when ambient light is present, the following procedure must be performed when taking spectroradiometric measurements of the phosphor chromaticities and luminances during the calibration. For each gun, first measure the tristimulus values (X,Y,Z) when the input voltage to the gun is zero and the brightness knob settings and ambient light conditions are exactly what they will be during the calibration and whenever colors resulting from the calibration are displayed. Subtract these tristimulus values from the corresponding tristimulus values obtained for each gun before calculating chromaticity coordinates (x,y) for the phosphor. For the luminances, measure the luminance when the input voltage is zero and subtract this value from all subsequent luminance measurements during the calibration. These procedures will ensure phosphor constancy despite the presence of background CRT light and/or ambient light.

B. The computational procedure.

The computational procedure for using the phosphor chromaticities and luminances to calculate the chromaticity of a displayed color will now be specifically described. The order of calculation follows the diagram in Figure 5A.

We start with the known monitor coordinates (R_C,G_C,B_C) of the displayed color C. We also know the stable chromaticities (x_R,y_R,z_R, x_G,y_G,z_G, x_B,y_B,z_B) of the three phosphors combining to produce C, from the initial spectroradiometric measurements. The goal, of course, is to obtain the tristimulus values (X_C,Y_C,Z_C) and chromaticity (x_C,y_C) of C. The displayed color, C, is a combination of various intensities of the three

phosphor primaries. Since the tristimulus values of a color that is the mixture of several components are the sums of the corresponding tristimulus values of those components, then for color C:

$$X_C = X_R + X_G + X_B \qquad (4a)$$

$$Y_C = Y_R + Y_G + Y_B \qquad (4b)$$

$$Z_C = Z_R + Z_G + Z_B \qquad (4c)$$

where the right-hand sides of the equations are the tristimulus values for the three phosphors when they combine to produce C.

The first step is to determine the luminance level of each of the three phosphors (Y_R, Y_G, Y_B) when they are producing C. These are obtained by linear interpolation from the initial calibration data, using the monitor coordinates (R_C, G_C, B_C). The second step is to determine the other tristimulus values (X_R, X_G, X_B, Z_R, Z_G, Z_B) for the three phosphors when they are producing C. Recall the defining equations 3a-c and note that the reverse transformation is:

$$X = (x/y)Y \qquad (5a)$$

$$Y = Y \qquad (5b)$$

$$Z = (z/y)Y. \qquad (5c)$$

We can now express the previously unknown X and Z tristimulus values as simple functions of known phosphor chromaticities (x_R, y_R, z_R, x_G, y_G, z_G, x_B, y_B, z_B) and calculated phosphor luminances (Y_R, Y_G, Y_B):

$$X_R = (x_R/y_R)Y_R \tag{6a}$$

$$X_G = (x_G/y_G)Y_G \tag{6b}$$

$$X_B = (x_B/y_B)Y_B \tag{6c}$$

$$Z_R = (z_R/y_R)Y_R \tag{6d}$$

$$Z_G = (z_G/y_G)Y_G \tag{6e}$$

$$Z_B = (z_B/y_B)Y_B. \tag{6f}$$

By substituting the values for X and Z in Eqs. 6a-f into Eqs. 4a and c, Eqs. 4 can be rewritten as:

$$X_C = (x_R/y_R)Y_R + (x_G/y_G)Y_G + (x_B/y_B)Y_B \tag{7a}$$

$$Y_C = Y_R + Y_G + Y_B \tag{7b}$$

$$Z_C = (z_R/y_R)Y_R + (z_G/y_G)Y_G + (z_B/y_B)Y_B. \tag{7c}$$

X_C, Y_C, and Z_C are now determined. Computationally it is most convenient to use matrix algebra and its notation to express the calibration procedure summarized in Eqs. 7a-c in a single calibration equation:

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} = \begin{pmatrix} x_R/y_R & x_G/y_G & x_B/y_B \\ 1 & 1 & 1 \\ z_R/y_R & z_G/y_G & z_B/y_B \end{pmatrix} \begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix}. \tag{8}$$

When this procedure is implemented in software to obtain the color's tristimulus values, it is only a matter of pre-multiplying the 3 x 3 matrix of phosphor chromaticities by the vector of phosphor luminances that is determined for each color. The phosphor chromaticity matrix need only be determined once for each calibration, while the phosphor luminances are calculated for each displayed color before the matrix multiplication. The

color's luminance is Y_C, and it has the same units as the original calibration measurements. Given the tristimulus values, it is now a simple matter to solve for the chromaticity coordinates (x_C, y_C) using Eqs. 3a and b. The color is thus completely specified.

II. <u>Determination of monitor coordinates needed to produce a specified chromaticity and luminance</u>.

The discussion so far has involved determining the chromaticity and luminance of a color displayed on a CRT. A second objective in calibrating a display is to solve the opposite problem of producing a color with a specified chromaticity and luminance.

A. <u>The computational procedure</u>.

In this situation, the goal is to obtain the necessary monitor coordinates (R_C, G_C, B_C) to produce a given color C with chromaticity coordinates x_C, y_C and luminance Y_C. The order of calculation follows the diagram in Figure 5B.

First, the third chromaticity coordinate (z_C) is obtained by subtracting x_C and y_C from 1.0. The other two tristimulus values for C (X_C, Z_C) are now available from Eqs. 5a and c using the desired chromaticities (x_C, y_C, z_C) and luminance (Y_C). The vector of tristimulus values in Eq. 8 is now known. The next step is simply to rearrange Eq. 8 so as to solve for the unknown phosphor luminances:

$$\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \begin{pmatrix} x_R/y_R & x_G/y_G & x_B/y_B \\ 1 & 1 & 1 \\ z_R/y_R & z_G/y_G & z_B/y_B \end{pmatrix}^{-1} \begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} . \qquad (9)$$

The 3 x 3 matrix needs to be inverted only with each new measurement of phosphor chromaticities. Then it is a matter of pre-multiplying this inverted matrix by the vector of calculated tristimulus values to obtain the desired phosphor luminances (Y_R, Y_G, Y_B). Given these, the monitor coordinates (R_C,G_C,B_C) can be determined using the original calibration data (Figure 4b), only *reversing* the direction of solution relative to the previous use. In other words, for each gun, a computer routine finds the luminance values that bracket the one in question and then interpolates to solve for the monitor coordinate. The voltages corresponding to these coordinates are now fed to the guns to produce the specified color at the specified luminance.

Acknowledgment. I thank Dr. James A. Worthey for introducing me to color measurement and color CRT calibration, and for demonstrating how much can be accomplished with knowledge of both.

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A simple calibration procedure for color CRT displays is described. It provides a convenient means of producing colors specified in terms of their chromaticity coordinates and luminance, as well as the inverse procedure -- determining the chromaticity and luminance of displayed colors to a reasonable degree of accuracy without direct measurement. It is intended for those with access to a spectroradiometer but with little or no background in color perception and measurement. A brief description of the commonly used 1931 CIE system of colorimetry is provided as background. References are provided for those desiring further information on the CIE system and issues affecting accurate color CRT calibration.

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